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Historically, the main product of the Sonar Array Survey System (SASS) has been bathymetry. There is, however, much more information available in the SASS data. The acoustic data available offer the possibility of geoacoustic characterization of the seafloor. Using information extractable from SASS data, the geoacoustic characterization may be accomplished by the estimation of parameters of proposed backscatter models. Proposed backscatter models are presented, and several are considered in relation to the SASS data. Given backscatter strength data and bathymetric data, the possibility of the estimation of parameters for these models is considered. The utility of the model is dependent on the ability to estimate the parameters of the model. It is obvious for this reason that models with parameters that are easily and reliably estimated are best for practical purposes.

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APPLICATION OF BACKSCATTER MODELS TO SASS

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Abstract

Historically, the main product of the Sonar Array Survey System (SASS) has been bathymetry. There is, however, much more information available in the SASS data. The acoustic data available offer the possibility of geoacoustic characterization of the seafloor. Using information extractable from SASS data, the geoacoustic characterization may be accomplished by the estimation of parameters of proposed backscatter models. Proposed backscatter models are presented, and several are considered in relation to the SASS data. Given backscatter strength data and bathymetric data, the possibility of the estimation of parameters for these models is considered. The utility of the model is dependent on the ability to estimate the parameters of the model. It is obvious for this reason that models with parameters that are easily and reliably estimated are best for practical purposes.

1 Introduction

This paper investigates the possibility of extracting more information from the SASS (Sonar Array Survey System) data by means of the estimation of parameters required for various backscatter models. Seafloor backscatter has long been of interest in sonar work because it acts as a major source of interfering reverberation. It is also of interest because it offers a means of remotely measuring characteristics of the seafloor. It is therefore important to know the dependence of backscattered reverberation on grazing angle, frequency, and bottom type [1]. Attempts have been made to relate the statistical properties of backscattered signals to independently observed geological characteristics of the seafloor. Changes in bottom type and roughness structure have been found to correlate with the acoustic backscattered signal. Potential has been shown for the possibility of using acoustic data obtained from a Sea Beam echo-sounder for means of seafloor characterization. The multi-narrow-beam geometry of both SASS and Sea Beam make the systems well suited for acoustic backscatter analysis because they both provide high angular resolution and quantitative estimates of apparent bottom slopes [2, 3].

Model parameter estimation will be based on data extractable from SASS. From SASS we know the measured backscattered strength and the bathymetry. From the bathymetric data the incident and azimuth angles can be determined. Table 1 summerizes parameter that can be directly extracted from the SASS data.

Table 1: Parameters extractable from SASS.

Symbol	Name
θ	grazing angle
θ_i	source incident angle
θ_s	receiver scattered angle
ϕ_i	source azimuth angle
ϕ_s	receiver azimuth angle
k	wavenumber

Current acoustic backscatter models vary in their governing parameters and complexity. Several of these models will be examined in their relation to the SASS data. A "good" model for this purpose would be a model whose parameters we could reliably estimate from the SASS data.

2 System Description

The Sonar Array Survey System (SASS), operated by the Naval Oceanographic Office (NAVOCEANO), is a hull-mounted system with a linear array of 144 hydrophones. SASS is a multibeam system that is able to map with high resolution a large swath of the seafloor with each traverse of the ship, as shown in

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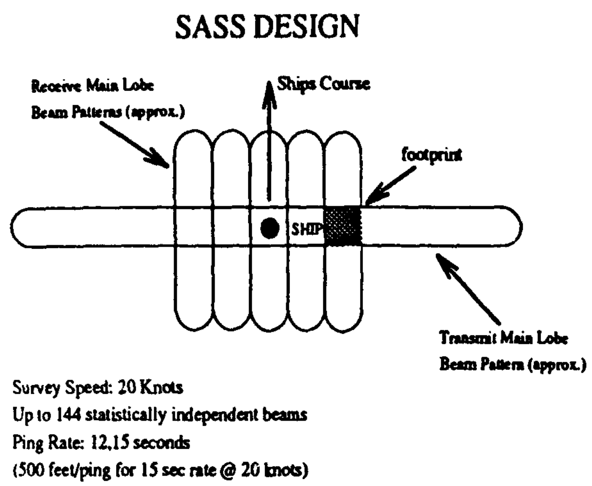

Figure 1: SASS geometry.

Figure 1. The system transmits at 12kHz and records the backscattering strength as a function of grazing angle. The SASS projector array insonifies the bottom of the ocean with a narrow beam of approximately one degree directed perpendicular to the ship's heading. The system receives the echo with 144 receiver hydrophones that are mounted athwartships (perpendicular to the projector), and spaced $\lambda/2$ apart, where λ is the nominal wavelength for 12kHz [4]. The SASS system has historically been used for bathymetry only; there is, however, much more information that can be extracted from the SASS data. Bathymetry is computed from the steering angle and the time of return of the echo. Earlier versions of SASS discarded the raw hydrophone data, so all amplitudes of the return signals were lost. A recent modification of SASS, however, records and saves the raw hydrophone data. It is from this raw hydrophone data that we are able to extract more information about the seafloor than just bathymetry. The acoustic data can be used for characterization of the seafloor. Information on the type of sediment and the roughness of the seafloor can be extracted from this acoustic profiling, and correlating this information to bathymetry will produce a powerful tool in thoroughly charting the seafloor.

3 Background on Modeling Backscatter

Urick presented [5] the backscatter of sound as a function of pulse length, frequency, and grazing angle. He introduced in 1954 a means of expressing these backscatter measurements in terms of a bottom scattering coefficient, called the "scattering strength," defined as follows: Given a sound wave incident on a small area dA of the bottom at a certain grazing angle θ, I_s is the backscatter intensity at a distance of one yard from dA back toward the source. The scattering strength of the bottom at an angle θ is the ratio of I_s to the incident intensity, per unit area of dA. The scattering strength is then the ratio of two intensities, the backscattered intensity and the incident intensity, and is related by the factor 2π to the backscattering cross section of unit area. This is given by

$$S = 10 \log \frac{I_{scat}}{I_{inc}} \tag{1}$$

The quantity "scattering strength" is commonly referred to as "backscattering strength."

Particle size is a factor in classifying bottoms in terms of acoustic backscattering. Urick, however, suggested that the roughness of the seafloor is the dominant determining characteristic for backscattering. Bottom type serves as a good indicator of bottom roughness.

We will now look at several semiempirical and theoretical models and their application to the estimation of the backscattering strength from SASS data.

4 Lambert's Rule

The fundamental model of backscatter strength is given by Lambert's rule, which states that the intensity I_s at a unit distance from dA due to the energy scattered at any angle θ is $\mu \sin\theta$ times this intensity, where μ is a constant particular to the diffusing surface. The physical basis of Lambert's rule provides that the brightness of an illuminated matte surface is almost equal regardless of the angle at which it is viewed [6]. Many rough surfaces satisfy Lambert's rule for both sound and light. Lambert's rule assumes that power is scattered proportionately to the sine of the angle of the scattering. Then, the intensity at unit distance in the direction φ will be

$$I_s = \mu I_i \sin\theta \sin\varphi dA \tag{2}$$

where μ is a proportionality constant. Taking 10 times the logarithm of each side of this function gives

$$10 \log \frac{I_s}{I_i} = 10 \log \mu + 10 \log(\sin\theta \sin\varphi) \tag{3}$$

and for collocated receiver/transmitter, $\varphi = \pi - \theta$, so

$$S_B = 10 \log \mu + 10 \log \sin^2\theta \tag{4}$$

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Table 2: Parameters of backscattered signal S_B.

Symbol	Name	Estimable from SASS
μ	constant particular to the diffusing surface	yes

In other words, the backscattering strength varies as the square of the sine of the grazing angle. Integration shows that $\mu = 1/\pi$ for the case where all of the incident acoustic energy is redistributed into the upper medium with none lost by transmission into the medium below. The backscatter strength for normal incidence is then $10\log(1/\pi) = -5$dB.

Many materials follow Lambert's rule closely in scattering of light, but none do so exactly. It is a good description of the backscattering of sound by some very rough bottoms[7]. The Lambert rule relationship has provided a good approximation to the data of many deep-water bottom studies of backscatter at grazing angles below about 45 degrees. Mackenzie [6] first demonstrated the relationship, and the parameter μ has come to be known as the Mackenzie coefficient. In 1961 Mackenzie introduced his analysis of bottom backscatter measurements assuming that the returned acoustic energy was comprised of both specular and nonspecular reflected sound. A portion of the sound returning from the bottom was assumed to be nonspecular reflections obeying Lambert's rule of diffuse reflection. The reverberation level due to this nonspecular reflection was analyzed to determine the scattering constant, μ, of the bottom, which varies with type of diffusing surface. Lambert's rule has provided the basis for many subsequent backscatter models.

4.1 Application of Lambert's Rule to SASS

Lambert's law is applicable to the SASS data. The parameters needed for estimation of backscatter strength given by Lambert's law are shown in Table 2. The grazing and azimuth angles can be calculated from bathymetry, and the returned backscatter strength is known. The only parameter that needs to be estimated then is μ, the constant particular to the diffusing surface. Knowing the grazing angle and the backscatter strength, calculation of μ is possible. Therefore, all parameters of Lambert's law are extractable from the SASS data. This makes Lambert's law a feasible model in the prediction of backscattering strength for the SASS system.

5 Marsh's Theory

Marsh generalized the method of Lord Rayleigh for a sinusoidal boundary for the case of a random surface [8]. Marsh's extension of Rayleigh's method produces an expression for the correlation function of the scattered field at two points in space in a horizontal plane below the examined rough surface [9]. The theory assumes a plane-wave solution and satisfies the boundary conditions by expansion in terms of the root-mean-square height of the surface [10]. This theory has typically been applied to sea surface scattering, but it applies to bottom scattering as well. The Marsh formula for the backscatter for a bottom transmitting no energy to the solid medium below is given by

$$S_B = 10\log\left[\frac{\sin^4\theta}{\pi\cos\theta}k^3A^2(K)\right] \tag{5}$$

where $A^2(K)$ is the amplitude squared of the irregularity of the bottom contour having wave number K. $A^2(K)$ is defined as the bottom-roughness power spectral density. The wave number k refers to the wavelength of the incident acoustic wave and the wave number K refers to the wavelength of a component of the bottom roughness. The wave number k is equal to $2\pi/\lambda_a$ given λ_a is the wavelength of the incident sound wave. Likewise, the wave number K is equal to $2\pi/\lambda_b$ given λ_b is the wavelength of a component of the bottom roughness. The Marsh theory treats the rough bottom as a diffraction grating for scattering where the scattering is mainly produced by that wavelength component of the bottom roughness for which phase reinforcement occurs for scattering back in the direction of the incident sound [7].

5.1 Application to SASS

Table 3 presents the parameters needed for the estimation of S_B for Marsh's formula. The grazing angle and wavelength of a component of the bottom roughness can be determined from the bathymetry, and the wavelength of the incident sound wave is known. So, given the grazing angle, λ_a, and λ_b, $A^2(K)$ can then be estimated. This fact makes Marsh's theory feasible in application to the SASS data.

Table 3: Marsh Theory Parameters of Backscattered Signal S_B.

Symbol	Name	Estimable from SASS
λ_a	wavelength of the incident sound wave	yes
λ_b	wavelength of a component of the bottom roughness	yes
$A^2(K)$	bottom-roughness power spectral density	yes

6 Patterson's Model

Patterson [11] developed a semiempirical roughness scattering model to describe data he took at 2.5kHz. Patterson investigates backscattering from four types of rough surfaces: acoustic backscattering from the ocean bottom and from the ocean surface, backscattering of radar from the ocean surface, and the backscattering of light from various surfaces. Two backscattering studies dealt with the radiation of underwater sound, and two dealt with electromagnetic waves. Patterson showed the similarities between these backscatter measurements and that of wave radiation from a rough boundary. These cases varied considerably in wavelength. Single coherent frequencies were used in all but the case of light, where the signal was incoherent. All cases varied in terms of their rough boundaries also. Patterson notes that in the case of the deep ocean it is extremely difficult, if not impossible, to measure the roughness of such a boundary. A more thorough understanding of the processes involved in seafloor backscattering is needed to overcome this difficulty. Despite the differences of the four cases considered, there are still notable similarities of the backscatter as a function of grazing angle. Patterson therefore suggested that it is possible to develop a mathemetical model of a rough surface as a backscatterer of wave radiation that is valid for the cases considered.

At low grazing angles, specular backscatter would be insignificant. Patterson represents specular reflection by some type of random probabilty density function. Patterson also considered the energy lost through the boundary. This energy cannot be backscattered and its loss can be represented in the model through the Rayleigh reflection coefficient. The three mechanisms Patterson considered in his model are the grazing angle, the specular reflection, and the loss at the boundary. These combine to give an estimate of the backscatter as

$$S_B = 10\log[A(B+C)], \qquad (6)$$

where A is the Rayleigh reflection coefficient, B is a constant times a random probability density funtion, and C is a constant times the sine of the grazing angle raised to some power [11]. The Rayleigh reflection coefficient helps account for bottom-reflection loss. Rayleigh derived the reflection loss of incident sound at an angle to a plane boundary between two fluids. This coefficient relates the intensity of the reflected wave I_r to the intensity of the incident wave I_i

$$R_0^2 = \frac{I_r}{I_i} = \left[\frac{m\sin\theta_1 - (n^2 - \cos^2\theta_1)^{1/2}}{m\sin\theta_1 + (n^2 - cos^2\theta_1)^{1/2}}\right]^2 \qquad (7)$$

where

$$m = \frac{\rho_2}{\rho_1} \qquad (8)$$

and

$$n = \frac{c_1}{c_2} \qquad (9)$$

The reflection loss is then $10\log I_r/I_i$. The values of the sound velocity ratio, c_1/c_2, and the density ratio, ρ_2/ρ_1, are needed to evaluate the Rayleigh reflection coefficient as a function of grazing angle. Brekhovskikh investigates the behavior of loss with the grazing angle for various conditions on m and n. The most common condition found for natural bottoms is that in which a critical angle θ_0 exists where total reflection occurs (zero loss) at grazing angles less than critical [7]. These two ratios have been shown to be highly correlated in their effect on the Rayleigh relflection coefficient, and this makes the ratios inseparable [12].

Patterson used his model to fit backscatter data from the ocean bottom. The constants required in the B parameter were chosen arbitrarily to fit the data and the expression 0.04 sin θ was used for C, which was also a fit to the data. A random distribution function was fit to the data for lower grazing angles, but not for higher ones since data was not readily available. The data fit the composite curve quite well, except for angles near normal incidence, where the angular resolution of the measuring technique was quite poor [11].

6.1 Application to SASS

Patterson's work serves as a good effort to construct a model that fits actual backscatter data. The parameters required for this semiempirical model are summarized in Table 4.

Table 4: Patterson's Model's Parameters of Backscattered Signal S_B.

Symbol	Name	Estimable from SASS
n	sound velocity ratio	no
m	density ratio	no
B	constant times some random pdf	no
C	constant times sine of grazing angle	no

We know the grazing angle, and do not know the sound velocity ratio and the density ratio. Due to the correlation of m and n in their effect on the Rayleigh reflection coefficient, it is not possible to independently estimate these ratios. If a simplifying assumption is made that these two parameters are linearly related, then estimation of one allows for estimation of the other. There is no physical basis for a linear assumption, but it has been shown [12] that when n is large m is also large. With this assumption, the Rayleigh coefficient can be estimated. We are able to estimate the parameters B and C by doing an arbitrary fit to the data. Patterson's model is therefore a feasible prediction model for use with the SASS data.

7 Modified Bistatic Scattering Strength Model (BISSM2)

The Modified Bistatic Scattering Strength Model was developed at the Naval Research Laboratory (NRL) with the support of the Advanced Acoustics Modeling Program (AUAMP). The following discussion of this model is based on the work of Caruthers et al. [13] and Bourgeois [12]. The scattering caused by bottom and subbottom fine-scale features (m_1) and the scattering caused by the large-scale bathymetric features (m_2) are added to define the total bistatic scattering strength m_{bs}

$$m_{bs} = m_1 + m_2 \tag{10}$$

The model defines m_1 as the incoherent scattered term and m_2 as the coherent term. The incoherent part, m_1, is given by Lambert's rule

$$m_1 = \mu \sin\theta_i \sin\theta_s \tag{11}$$

where θ_i is the source incident angle, θ_s is the receiver scattered angle, and μ is the MacKenzie coefficient. This coefficient can be determined empirically or by geomorphic ananlyses. The coherent part, m_2, is governed in part by the Rayleigh reflection coefficient between two fluids, the Rayleigh roughness parameter,the RMS micro-scale roughness, the fine-scale RMS slopes in the x and y directions, θ_s, and θ_i. The coherent scattering is given by

$$m_2 = R_0^2 \exp(-g)\frac{F^2}{2\pi\delta_x\delta_y} \exp - \left[\frac{1}{2q^2}\left(\frac{X_x^2}{\delta_x^2} + \frac{X_y^2}{\delta_y^2}\right)\right] \tag{12}$$

where R_0 is the Rayleigh reflection coefficient between two fluids. The two fluids have a density ratio of m and a sound speed ratio of n. The parameter g is given by

$$g = \sigma^2 q^2 \tag{13}$$

where σ is the RMS micro-scale roughness and

$$q = k[\sin\theta_i + \sin\theta_s] \tag{14}$$

where k is the acoustic wavenumber. g is the square of the Rayleigh parameter. δ_x and δ_y are the fine-scale RMS slopes in the x and y directions, given by

$$\delta_x^2 = \frac{1}{n^2}\sum_{i=1}^{n}\sum_{j=1}^{n}(\delta_x^{ij})^2 \tag{15}$$

$$\delta_y^2 = \frac{1}{n^2}\sum_{i=1}^{n}\sum_{j=1}^{n}(\delta_y^{ij})^2 \tag{16}$$

where n is the number of points along one side of a square grid and δ_x^{ij} and δ_y^{ij} are the incremental change in slope in the x and y directions.

The parameter F is given by

$$F = \frac{1}{2}\left(1 + \frac{X^2}{q^2}\right) \tag{17}$$

where X is given by

$$X^2 = X_x^2 + X_y^2 \tag{18}$$

and

$$X_x = k(\cos\theta_s \cos\phi_s - \cos\theta_i \cos\phi_i) \quad (19)$$

$$X_y = k(\cos\theta_s \sin\phi_s - \cos\theta_i \sin\phi_i) \quad (20)$$

The monostatic version of this model is given in [12] by

$$m_{ms} = \mu \sin^2\theta + \frac{R_0^2 \exp(-g)}{8\pi\delta^2 \sin^4\theta} \exp\left(-\frac{\cot^2\theta}{2\delta^2}\right) \quad (21)$$

7.1 Application to SASS

Now we will consider the estimation of the BISSM parameters given the backscatter strength and bathymetric data. The parameters required by the model are summarized in Table 5.

Table 5: BISSM Parameters of Backscattered Signal m_{ms}.

Symbol	Name	Estimable from SASS
R_0	Rayleigh reflection coeficient	yes
μ	Mackenzie coefficient	yes
σ	RMS micro-scale roughness	yes
δ_x	fine-scale RMS slopes in x direction	yes, given $\delta_x = \delta_y$
δ_y	fine-scate RMS slopes in y direction	yes, given $\delta_x = \delta_y$

Bourgeois [12] has investigated the estimation of these parameters given artificially collocated bathymetric and backscatter data. We will follow his discussion of the estimation of these parameters. Directly extractable from SASS are the angles θ and ϕ; these can be determined from the bathymetric data and the source ray trace angle. The wave number k can be determined from the source frequency and the local speed of sound in water. The parameters that need to be estimated are therefore $n, m, \mu, \sigma, \delta_x$, and δ_y. Bourgeois empirically determines the correlation between these parameters in efforts to identify which parameters may be potentially estimated.

The dependence of backscatter on the MacKenzie coefficient, μ, was investigated. It was found that an increase in μ causes a fairly uniform increase of backscatter strength for lower incident angles (less than 70 degrees). Bourgeois then estimates the MacKenzie coefficient using neural networks and an artificial input data vector of scattering strength vs. incident angle. The SASS data provides us with values for scattering strength and incident angle, therefore we are able to estimate the MacKenzie coefficient.

The effect of backscatter strengths due to variations of m and n show that these parameters are highly correlated, so m and n should not be independently estimated. A simplifying assumption can be made that m and n are linearly related, since n is large when m is large. This assumption allows for the estimation of the Rayleigh reflection coefficient using only one parameter, either m or n. Employing a neural network that uses as input a vector of scattering strength vs. angle of incidence, Bourgeois estimates the m parameter, and from this, n can be indirectly estimated based on the assumption of a linear relationship. There is no physical justification for the assumption of a linear relationship however. With this assumption though, the Rayleigh reflection coefficient can be estimated. This argument can be applied to SASS, so we can conclude that the Rayleigh reflection coefficient is estimable from SASS.

Effects on backscatter strength due to variations in δ_x and δ_y are found to be highly correlated. These parameters therefore cannot be estimated independently. Bourgeois then makes a simplifying assumption that $\delta = \delta_x = \delta_y$, and estimates this single parameter. With this assumption, the effect of the parameter ϕ vanishes.

Variations in backscatter strength due to changes in σ are found to be highly correlated with those due to changes in m and n. Furthermore, these changes are relatively small except at higher frequencies. SASS operates at 12kHz which allows for a reasonable estimation of σ, but only if n and m are assumed known constants.

The only parameters that have the potential of being independently estimated are μ and δ. This conclusion can be extended to apply to the SASS data. The BISSM equation serves well as a theoretical model, but it is not readily applied to SASS.

8 Summary

We have considered four models to be used for parameter estimation with the SASS data. The first was

Lambert's rule, which we found to be applicable to the SASS data. Next, we looked at Marsh's theory, which is a generalization of Rayleigh's method. This theory, too, is applicable to the SASS data. The third model was Patterson's model, which was a semi-empirical fit to data. His model took into account the reflection loss between two mediums. An arbitrary fit to data allows for application of this model. And finally, a review of the BISSM equation showed that it is a reasonable theoretical model, but is not readily applicable to SASS.

It is desirable to use a model where the parameters of the model can be estimated given knowledge of the backscatter strength and the bathymetric data. This would allow for the geoacoustic chararacterization of the seafloor. The number of parameters of the model, however, should be the same as the number of degrees of freedom of the data for good invertability. Essentially, the model parameters should be limited to those parameters that affect the measured backscattered strength. Parameters that make little or no difference on the backscatter strength can be neglected without significant introduction of error. This limitation simplifies the inversion problem of estimating parameters of the backscatter strength models. It is also desirable for the parameters to be uncorrelated so that they can be independently estimated. For these reasons, models such as Lambert's, Marsh's and Patterson's lend themselves well to parameter estimation. Lambert's simplicity allows for inversion, which gives us knowledge of one parameter descriptive of the ocean bottom. Inversion of Marsh's theory gives us slightly more information about the nature of the bottom, as does Patterson's through a fit to the data. The more parameters a model has, the more information is potentially gained. This is only useful if the parameters can be estimated. The most complicated model, BISSM, potentially offers the most information about the nature of the bottom. The model is not readily invertable given SASS data, so we are unable to extract the information the parameters offer. Hence, we are best off using a simpler model whose few parameters we are able to estimate with some degree of certainty, though more complicated models potentially offer more information.

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